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Increasing performance and energy efficiency of Gas Metal Arc Welding by a high power tandem process

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Abstract

Standard Gas Metal Arc Welding (Standard GMAW) and a high power Tandem GMAW (TGMAW) process are evaluated with respect to energy efficiency. Current, voltage and overall equipment power are measured and energy consumption is determined. The new key performance indicator Electrical Deposition Efficiency is introduced to reflect the energy efficiency of GMAW processes. Additionally, wall-plug efficiency of the equipment is determined in order to identify the overall energy consumption. Results show that energy efficiency as well as economic process performance can be significantly increased by application of the TGMAW process. Furthermore findings indicate that wall-plug efficiency of the equipment is independent of power level and material transfer mode. A metal plate of 30 mm thick structural steel is joined by Standard GMAW and TGMAW to demonstrate the total energy savings for a real weld. Electricity consumption is reduced by more than 20 % using the high power TGMAW process.

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1. Introduction

Sustainable development and climate change mitigation both demand for resource efficient production [1, 2]. Generally, welding is the most important joining technology in manufacturing, whereas Gas Metal Arc Welding (GMAW) is one of the most frequently applied processes [3]. Especially in the steel constructing sector, arc welding accounts for a main share of the total costs and the energy consumption in manufacturing [4]. Furthermore, previous studies have shown that apart from filler material, electricity dominates the environmental burdens of GMAW [5]. So far, energy efficiency of GMAW has been neglected by the industry [4, 6, 7]. This is mainly due to the focus on economic process performance, which has been intensively pushed forward in the last decades. Typically, cost efficient GMAW is executed in the spray arc operation mode. Therefore the present study applies the spray arc transfer as the reference GMAW process (Standard GMAW). Further increase of productivity can be achieved by a Tandem GMAW (TGMAW) process. TGMAW, mostly operated in a pulsed-spray transfer mode, reaches significantly higher deposition rates and welding speeds, which are the main indicators of economic performance. However, process parameters have to be chosen carefully to prevent process instabilities [8-12].

Energy consumption is closely related to the energy flows of the GMAW process, which are described in detail in literature [13-20]. Among all efficiency indicators presented, the effective efficiency has the biggest influence on the energy consumption of GMAW. This is because it determines the relative amount of energy that can be used for melting the wire and the base material. In [15] and [18], the influence of several process parameters and the material transfer mode is studied. Bosworth [15] found that for the same deposition rate, pulsed instead of non-pulsed welding demanded a lower process power, which favors pulsed welding in terms of energy efficiency. Haelsig et al. [18] observed a higher effective efficiency for TGMAW in contrast to Standard

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GMAW and thus indicate an increased energy efficiency of TGMAW. Pépe et al. [14] and Haelsig [21] discovered that for several GMAW processes the needed process power for a certain material deposition rate varies significantly despite similar effective efficiencies. Consequently, these findings state that the effective efficiency does not serve as a sufficient measure for energy efficiency and that the absolute process power demand has to be taken into account. Additionally, effective efficiency of high power GMAW has not been under investigation before since deposition rates of all prior works (with the exception of Haelsig with 12 kg/h [18]) do not exceed 8 kg/h.

Another indicator apart from the effective efficiency was studied by Chandel [20] for Standard GMAW. The investigated electrode melting efficiency determines the amount of molten filler material relative to the theoretical amount that can be molten with the energy supplied by the arc. It was shown that more filler material can be molten per unit of process power when welding with higher currents, enlarged contact tube to workpiece distance and negative electrode polarity. Thus, results suggest high welding powers in order to enhance energy efficiency.

First and recent works with reference to the energy consumption of GMAW were done by Huismann and Burt [22] and Hübner et al. [23]. Hübner et al. are using a third wire in a TGMAW process to reduce the burn off rate of alloy elements and stabilize the process. Stated efficiencies are between 594 g/kWh for the regular TGMAW process and 833 g/kWh for the three wire process. However, a comparison to a Standard GMAW process or specific parameter influences are missing. Huismann and Burt are focusing on the energy input into the weld metal without considering electricity consumption. Instead, the specific power input is calculated in order to define a hot or cold process and consequently choose the proper welding conditions.

In summary, energy consumption of GMAW, especially high power GMAW, has not been intensively studied before. In addition, literature does not provide a clear definition for an energy efficiency indicator that can be applied to process parameters.

This paper aims on evaluating the energy efficiency of GMAW. It is done by measuring the energy consumption and calculating the respective key performance indicator electrical deposition efficiency. Two processes are under survey, a Standard GMAW process and a TGMAW process. Finally, a 30 mm thick metal plate is joined to determine energy consumptions for a real joint. On the one hand, this will support industry with an indicator for energy oriented process development. On the other hand, it states how process performance and energy efficiency can be increased at the same time, which will lead to reduced manufacturing costs and reduced environmental impacts of welding.

2. Methodology

2.1. Process data acquisition

Energy consumption was assessed by power measurements at two positions. As shown in Fig. 1, current and voltage are measured before and after the welding power source.

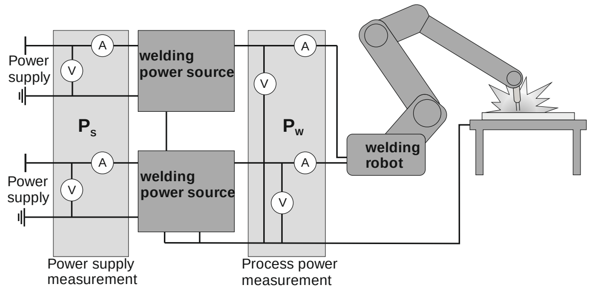

Fig. 1. Schematic diagram of the power measurement system

The power supply measurement evaluates the total power P_S including secondary consumptions, e.g. from the wire feeder. P_S is used to calculate the wall-plug efficiency of the equipment and to determine the overall energy consumption. A commercial measurement system was applied to measure and record current and voltage of the three phases separately between the power supply and the welding power sources. P_S was calculated according to equation (1) by the sum of the effective powers of each of the three phases [24]. P_{S1} ,P_{S2} ,P_{S3}, were provided directly by the measurement system.

$$P_s = P_{s1} + P_{s2} + P_{s3} \tag{1}$$

The process power P_W quantifies the energy that is needed by the process to create the weld pool and to melt the wire. P_W enables investigation of the process parameters and provides information about the stability of the process. Furthermore, disturbances from the equipment (e.g. chiller, inner circuit power etc.) can be excluded. Current I and voltage U were measured and recorded with a commercial data acquisition system. P_W was calculated according to equation (2) as the arithmetic mean value of the instantaneous power [15]. The wall-plug efficiency of the equipment η is calculated by equation (3).

$$P_W = \frac{1}{t}\int_0^t I(t) \cdot U(t)\, dt \tag{2}$$

$$\eta = \frac{P_W}{P_S} \tag{3}$$

2.2. Electrical Deposition Efficiency

The Electrical Deposition Efficiency (EDE) serves Efficiency (EDE) serves as a key performance indicator for the energy efficiency of a GMAW process in contrast to the indicator presented by Huismann and Burt [22] who just focused on heat input into the filler material. It evaluates the mass of molten filler material per unit of electricity consumption. It is stated in equation (4) by using the process parameters wire feed rate wfr, process power P_W, the wire electrode cross-section area A_W, and the density of the filler material ρ.

$$EDE = \frac{wfr}{P_W} \cdot \rho \cdot A_W \quad \text{in g/kWh} \tag{4}$$

The indicator EDE is mainly affected by the absolute process power and the effective efficiency, which integrates plenty of influences like shielding gas, material transfer mode or the distance between the contact tube and the workpiece. Furthermore, the process power depends on the welding power source characteristic and the process parameter setting. The present study evaluates the EDE for a Standard GMAW and a TGMAW process. The TGMAW process adopts a different material transfer mode and adjusted process parameters for enhanced energy efficiency.

In contrast to the effective efficiency, EDE is an absolute quantity that is directly related to the energy consumption. Consequently, the required energy for a given weld can be calculated. The determination of the absolute electricity consumption E for a weld of the mass m is shown in equation (5) by applying the wall-plug efficiency η.

$$E = \frac{m}{EDE \cdot \eta} \quad \text{in kWh} \tag{5}$$

2.3. Conduction of experiments

Welding was performed automatically in the flat position by a welding robot. Welding samples were made of 30 mm thick structural steel plates. The specimen were prepared with a V-groove, a ceramic backing plate and tack welded. The filler material was a proper standard wire electrode with a diameter of 1.2 mm. Data was measured by executing the multi-pass weld. Assumed steel density of the wire electrode was 7.85 g/cm³.

In the first set of experiments, EDE was evaluated for two power levels of the Standard GMAW (Standard GMAW 1 and 2) and the TGMAW (TGMAW 1 and 2) process. Every parameter set was executed 2 to 7 times to assure the quality of the results. Current and voltage data sets were analyzed for 20 s to 30 s of a stable process condition. The process power P_W as well as the overall power P_S were calculated according to equation (1) and (2).

Table 1 shows the experimental conditions of the Standard GMAW process. The welding parameters were set by the synergic characteristic of the welding power source according to the selected wire feed rate. The operation mode for Standard GMAW was spray arc transfer.

Table 1.Experimental conditions of the Standard GMAW process

	Standard GMAW 1	Standard GMAW 2
Wire feed rate in m/min	12 (6.4 kg/h)	14 (7.5 kg/h)
Welding speed in mm/s	6.7	7.5
Average process power P_W in kW	11.8	13
Type of shielding gas	82 % Ar, 18 % CO_2	82 % Ar, 18 % CO_2
Contact tube to workpiece distance in mm	18	18

Table 2 lists the experimental conditions of the TGMAW process, which was operated with a pulsed-spray transfer. The pulse frequencies of the electrodes were adjusted according to the wire feed rate and independent from each other (asynchronous pulses). The further process parameters (base current, pulse voltage and pulse duration) were set with respect to the process quality and a minimal process power P_W.

Wall-plug efficiencies of the welding power sources were calculated for every process according to equation (3) and by applying P_W and P_S.

Table 2. Experimental conditions of the Standard GMAW process

	TGMAW 1	TGMAW 2
Wire feed rate in m/min	27.5 (14.7 kg/h)	35 (18.7 kg/h)
Welding speed in mm/s	11.7	13.3
Average process power P_W in kW	20.9	23.8
Type of shielding gas	92 % Ar, 8 % CO_2	92 % Ar, 8 % CO_2
Contact tube to workpiece distance in mm	20	20

In the second set of experiments, a complete butt joint was welded for Standard GMAW and TGMAW for determination of overall electricity consumption. The weld seam length was 600 mm and results are scaled to 1 m for better comparability. For Standard GMAW a stringer bead technique and for TGMAW a weaving bead technique was applied. Root pass welding for the TGMAW variant was executed with single wire GMAW. The final pass of the TGMAW weld used a reduced process power to prevent weld defects in the top layer. Experimental conditions of the Standard GMAW and the TGMAW butt joints are shown in Table 3. Overall electricity consumption was determined by recorded current and voltage data and the measured wall-plug efficiency of the welding power sources. The electricity consumption for both variants was adjusted to an equal mass of deposited filler material. This was done to exclude effects from geometry deviations that origin from flame cut grooves or the weld reinforcement.

Table 3. Experimental conditions of butt joint welding

	Standard GMAW	TGMAW
Wire feed rates in m/min	Root pass: 10 Filler passes: 12.5	Root pass: 12.5 Filler passes: 20-35
Average welding speed in mm/s	6.7	6.4
Average process power P_W in kW	Root pass: 9.8 Filler passes: 11.7	Root pass: 9.6 Filler passes: 21.6
Groove preparation	V (ISO 9692-1) 55° groove angle 1 mm root gap 2 mm root face	V (ISO 9692-1) 55° groove angle 1 mm root gap 2 mm root face
Base material (DIN EN 10025-3)	S355 J2+N	S355 J2+N
Filler material (DIN EN ISO 14341-A)	G 4Si1	G 4Si1

3. Results

3.1. Electrical Deposition Efficiencies

Fig. 2 shows the results of the EDE measurements. The high power TGMAW process achieves significant higher values than the Standard GMAW process.

Mean EDE values of the Standard GMAW process are between 541 g/kWh and 571 g/kWh. The TGMAW process reaches mean values between 701 g/kWh and 783 g/kWh. Standard deviations of measured EDE is generally low for all variants but higher for the TGMAW process. Both processes tend to give higher EDE values with higher wire feed rates and process powers.

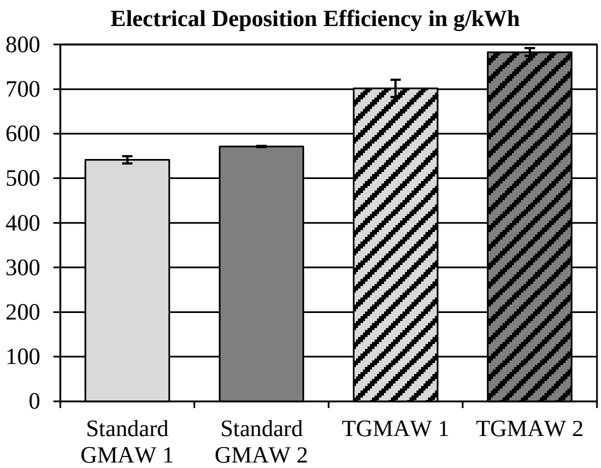

Fig. 2. Results of the EDE measurements

3.2. Wall plug efficiencies

Fig. 3 displays the measured wall-plug efficiencies of the process variants, which are all on a constant level. Wall-plug efficiencies of the Standard GMAW processes are between 84.6 % and 84.9 %. Similar values were measured for the TGMAW variants ranging from 83.6 % to 86.7 %. Standard deviations of all measurements are below 0.5 %. A dependency of the wall-plug efficiency on the material transfer mode (spray or pulsed spray) can not be observed. Furthermore an influence of the process power P_W can not be detected.

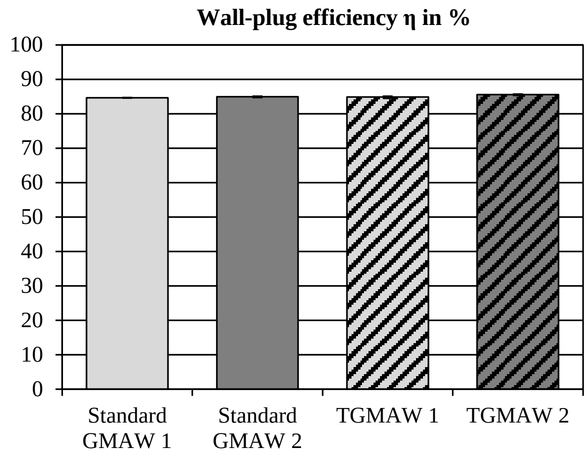

Fig. 3. Results of the wall-plug efficiency measurements

3.3. Electricity savings for a real weld

A 30 mm thick metal plate was joined to demonstrate potential electricity savings for a real weld. Cross-sections of the Standard GMAW and TGMAW butt joints are displayed in Fig. 4. Process performance data is listed in Table 4.

Table 4. Results of the butt joint welds for 1 m weld seam

	Standard GMAW	TGMAW
Overall electricity consumption in kWh	8.7	6.7
Filler material consumption in g	4457	4200
Average EDE in g/kWh	568	735
Welding time in min	40	18
Number of passes	16	6

Figures for electricity consumption, welding time and filler material consumption are scaled to a weld seam length of 1 m. Applied wall-plug efficiency for overall energy consumption was 85 %. Measured average EDE values of both processes are in agreement with the results in section 3.1. The Standard GMAW process consumed more filler material due to the higher weld reinforcement (see Fig. 4 a) and possible geometry deviations resulting from groove preparation or tack welding. Therefore electricity consumption was adjusted to the minimal amount of filler material. This was done by using the respective EDE values and the filler material consumption of the TGMAW process (4200 g). The full potential of the high power processes presented in section 3.1 could not be realized in the root and final pass due to the risk of defects.

As stated in Table 4, energy efficiency as well as process performance are both increased by applying the TGMAW process. Electricity consumption and welding time are reduced by 23 % and 55 %.

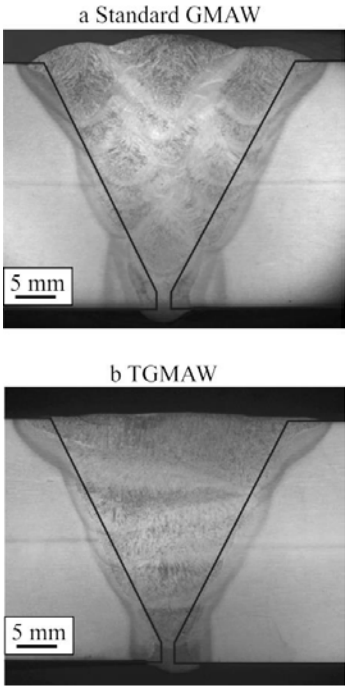

Fig. 4. Cross-section of the (a) Standard GMAW and the (b) TGMAW joint

4. Discussion

Presented results are consistent with expectations based on the literature research (see section 1) and confirm its indications regarding the energy efficiency of GMAW. On the one hand, the higher energy efficiency of TGMAW in contrast to Standard GMAW results from the higher effective efficiency of the pulsed tandem process. This is mainly because of the material transfer mode, which leads to less heat losses in the arc for the TGMAW process. Additionally, it can be observed that findings of Bosworth [15] and Haelsig et al. [18] are still valid for higher process powers and deposition rates. However, the effective efficiency does not provide justification for all of the results. Within the scope of the investigations, higher process powers yielded a higher energy efficiency for Standard GMAW as well as TGMAW. Based on [13, 15, 19], higher arc powers lead to more heat losses in the arc from convection and radiation and thus to lower effective efficiencies. Hence, the heat losses have to be compensated by other effects. An explanation of this issue is provided by the higher electrode melting efficiency with higher process powers that was presented by Chandel [20]. Consequently, higher process powers increase the energy efficiency of GMAW despite the reduced effective efficiency.

On the other hand, the absolute needed process power is dependent on the source characteristic and the parameter settings which can be with respect to energy efficiency, expressed as the EDE in g/kWh. As presented, adjusting welding parameters to the energy demand of the process leads to significant improvements.

Presented values for the EDE can be well integrated with the findings of Hübner et al. [23]. The value for a TGMAW process in their work is 594 g/kWh and thus significantly lower than the figures for TGMAW shown in the present study. One reason for the higher values is the operation mode with asynchronous pulses in contrast to synchronized pulses used by Hübner et al.. Asynchronous pulses allow separate control of process parameters for both electrodes, which can then be optimized with respect to energy efficiency. Additionally, deposition rates and consequently power ranges were lower which can be a reason for the observed process behavior. The EDE values of Hübner et al. are slightly higher than for Standard GMAW because of the higher effective efficiency.

Wall-plug efficiencies of the welding power sources are on the same level as published by Haelsig [21]. Higher energy efficiency of a process leads directly to less electricity consumption as there is no effect of the material transfer mode or the process power. Still, around 15 % of the electricity is not used for welding but secondary functions. Therefore, future studies shall focus as well on the wall-plug efficiency of welding power sources.

Experiments of butt joint welding demonstrated the potentials of TGMAW. Economic performance, mainly represented by welding time, as well as energy efficiency for thick metal plate welding was enhanced. Due to the weaving bead technique, the welding speed remained on a moderate level. Advantages of the weaving bead technique are the reduced number of passes and hence a minimized risk of incomplete fusion and slag inclusion. However, the high process powers and the moderate welding speeds lead to high heat inputs in the filler passes, which could deteriorate the material properties. Therefore, future studies shall also focus on weldability and ensure material properties of welds made by the TGMAW process.

5. Conclusions

Energy efficient manufacturing technologies are an essential instrument for climate change mitigation and sustainable manufacturing. GMAW, one of the most frequently applied joining technologies, has been characterized with respect to energy consumption and efficiency. This will enable industry to design more energy efficient welding procedures and allows detailed planning of the energy consumption of part manufacturing.

A data acquisition system has been set up to measure electricity consumption including and excluding the equipment. As a gauge for measuring and controlling, the key performance indicator EDE was defined.

EDE of Standard GMAW and an TGMAW process have been evaluated for two power levels. Generally the TGMAW process reaches higher values for EDE than Standard GMAW, whereas both processes show a higher energy efficiency on the higher power level. Additionally, the TGMAW process reaches much higher deposition rates and thus process performance. Wall-plug efficiency of the equipment was independent of the material transfer mode and the process power. Furthermore, potentials of the TGMAW process were demonstrated on butt joints of 30 mm thick steel plates. Energy consumption and welding time were reduced by 23%

and 55%, respectively. In summary, the TGMAW process enables higher energy efficiency and economic performance at the same time.

Based on the presented results, further research towards increased energy efficiency of GMAW require intensive studies concerning the influence of the operation mode, power ranges and process parameters on the EDE. Especially the dependencies between process power and energy efficiency has to be studied further. Finally the improved processes have to be qualified for the application in industry.

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